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13. ABSTRACT (Maximum 200 words) The purpose of this project has been to address the issue of informational complexity by developing adaptive structures that can achieve the performance advantages of multiuser detection, without the attendant need for special knowledge about the signal environment. A major achievement has been the development of an optimally near-far resistant blind adaptive algorithm which requires no more knowledge than a conventional single-user matched filter.				
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Final Report of ARO Grant DAAH04-93-G-0219

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Princeton University

May 18, 1997

A. Statement of the Problem Studied

The scientific objective of the project "Adaptive Multiuser Demodulation" (ARO Grant DAAH04-93-G-0219) was to establish general principles for adaptive interference mitigation for digital demodulation in multiple-access systems. We summarize briefly some of the salient findings from this investigation, referring the reader to the listed publications for details.

The primary approach of ARO Grant DAAH04-93-G-0219 has been concerned with multiuser detection; i.e., the optimal and sub-optimal demodulation of digital communication signals in a non-orthogonal multiplex. This general problem area has been a subject of intense study for more than a decade, and the key previous results have shown that significant performance improvement (over conventional systems) can be had if multiple-access interference is not neglected. A major disadvantage of optimal multiuser detection techniques is their complexity, both in the traditional sense of computational complexity, and in the sense of *informational* complexity, which refers to their need to know signaling information not needed by conventional techniques. A considerable amount of previous work has been directed at the development of low (computational) complexity algorithms for near-optimal multiuser detection.

B. Summary of the Most Important Results

The purpose of ARO Grant DAAH04-93-G-0219 has been to address the issue of informational complexity by developing adaptive structures that can achieve the performance advantages of multiuser detection, without the attendant need for special knowledge about the signaling environment.

A major achievement has been the development of an optimally near-far resistant blind adaptive algorithm which requires no more knowledge than a conventional single-user matched filter. This receiver (41) converges to the minimum mean-square error linear multiuser solution without having to know anything about the codes, received amplitudes or delays of the interferers. par Many of the results obtained under this contract are

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reviewed in (9), (12), (15), (35), (43).¹ Among these approaches are parameter-adaptive algorithms featuring joint data-detection and parameter estimation (7), (24), (25), (26); combined suppression of multipath and co-channel interference (1), (39), (47) least-squares and neural-network based adaptive algorithms requiring training sequences (22), (23), (30), (32); and demodulator update algorithms based on the detection or discrimination of new users entering the network (10), (13), (14), (17), (18), (19), (27). Also, several analytical techniques for performance evaluation of certain multiuser detection algorithms have been developed (6), (16), (20), (28), (31). Multiuser detection has also been applied to the suppression of digital narrowband interference (5), (11), (21), (29), showing considerable performance improvement over prior predictive methods. These latter results have lead to recent results, reported in (3) - (5), which deal with the general problem of combined blind adaptive suppression of multiple-access interference and narrowband interference, and with the parallelization of algorithms for this purpose.

C. List of Publications Supported under DAAH04-93-G-0219

1. X. Wang and H.V. Poor, "Adaptive Joint Multiuser Detection and Channel Estimation for Multipath Fading CDMA Channels," To appear *ACM Wireless Networks - Special Issue on Multiuser Detection in Wireless Communications*.
2. X. Wang and H.V. Poor "Adaptive Multiuser Diversity Receivers for Frequency-selective Rayleigh Fading CDMA Channels," In *Proceedings of the 1997 IEEE Vehicular Technology Conference*, May 5 - 7, 1997, Phoenix, AZ.
3. X. Wang and H.V. Poor, "Code-aided Interference Suppression in DS/CDMA Spread-spectrum Communications - Part I: Interference Suppression Capability," To appear in *IEEE Transactions on Communications*.
4. X. Wang and H.V. Poor, "Code-aided Interference Suppression in DS/CDMA Spread-spectrum Communications - Part II: Parallel Blind Adaptive Implementations," To appear in *IEEE Transactions on Communications*.
5. X. Wang and H.V. Poor, "Adaptive Suppression of Narrowband Digital Interferers from Spread-spectrum Signals," To appear in *Wireless Personal Communications - Special Issue on Interference in Mobile Wireless Systems*.
6. S. Verdú and H.V. Poor, "Probability of Error in MMSE Multiuser Detection," *IEEE Transactions on Information Theory*, Vol. 43, No. 3, pp. 858 - 871, May 1997.
7. L.B. Nelson and H.V. Poor, "Iterative Multi-user Receivers for the Synchronous CDMA Channel: An EM-Based Approach," *IEEE Transactions on Communications*, Vol. 44, No. 12, pp. 1700 - 1710, December 1996.

¹Numbers enclosed in parentheses (e.g., (1)) refer to ARO-supported publications listed in Section C.

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8. X. Wang and H.V. Poor, "Adaptive Multiuser Detection in Fading Channels," (invited paper, In *Proceedings of the 1996 Allerton Conference on Communications, Computing, and Control*, University of Illinois, October 2 - 4, 1996.
9. X. Wang and H.V. Poor, Invited paper, "Signal Processing for Adaptive Interference Suppression in CDMA Systems" In *Proceedings of the 5th ESA International Workshop on DSP Applied to Space Communications*, Barcelona, Spain, September 25 - 27, 1996.
10. U. Mitra and H.V. Poor, "Activity Detection in a Multi-user Environment," *Wireless Personal Communications Special Issue on Signal Separation and Interference Cancellation for Personal, Indoor and Mobile Radio Communication*, Vol. 3, pp. 149 - 174, 1996.
11. X. Wang and H.V. Poor, Invited Paper, "Adaptive Suppression of Narrowband Digital Interferers in Spread-spectrum Networks," *Proceedings of the 1996 IEEE International Conference on Acoustics, Speech and Signal Processing*, Atlanta, GA, May 1996.
12. H.V. Poor, Invited Paper, "Adaptive Interference Suppression in CDMA Systems," *Proceedings of the Symposium on Interference Rejection and Signal Separation in Wireless Communications*, New Jersey Institute of Technology, Newark, NJ, March 19, 1996.
13. U. Mitra and H.V. Poor, "An Adaptive Decorrelating Detector for Synchronous CDMA Channels," *IEEE Transactions on Communications*, Vol. 44, No.2, pp. 257 - 268, February 1996.
14. U. Mitra and H.V. Poor, "Adaptive Decorrelating Detectors for CDMA Systems," (with Urbashi Mitra). *Wireless Personal Communications*, Vol. 2, pp. 415 - 440, 1996.
15. H.V. Poor, Invited Paper, "Adaptivity in Multiple-access Communications," *Proceedings of the 34th IEEE Conference on Decision and Control*, New Orleans, LA, December 13-15, 1995, pp. 835 - 840.
16. S. Verdú and H.V. Poor, "A Lower Bound on the Probability of Error in Multihypothesis Testing," *IEEE Transactions on Information Theory*, Vol. 39, No. 6, pp. 1992 - 1994, November 1995.
17. U. Mitra and H.V. Poor, "Detection of Spread-spectrum Signals for Linear Multi-user Receivers," *Proceedings of the 1995 IEEE International Symposium on Information Theory*, Whistler, BC, Canada, September 17 - 22, 1995.

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18. U. Mitra and H.V. Poor, "Adaptive Decorrelating Detectors for CDMA Channels," *Proceedings of the 1995 IEEE International Conference on Communications*, Seattle, WA, June 18 - 22, 1995.
19. U. Mitra and H.V. Poor, "Detection of Spread-spectrum Signals in a Multi-user Environment," *Proceedings of the 1995 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP95)*, Detroit, MI, May 8 - 12, 1995.
20. H.V. Poor and S. Verdú, Invited, "On the Bit-error Rate of MMSE Multiuser Detection," *Proceedings of the 1995 IEEE Workshop on Information Theory, Multiple Access and Queueing*, St. Louis, MO, April 19 - 21, 1995.
21. L.A. Rusch and H.V. Poor, "Multiuser Detection Techniques for Narrowband Interference Suppression in Spread-spectrum Communications," *IEEE Transactions on Communications*, Vol. 43, No. 2/3/4, Part III, pp. 1725 - 1737, February/March/April 1995.
22. U. Mitra and H.V. Poor, "Adaptive Receiver Algorithms for Near-far Resistant CDMA," *IEEE Transactions on Communications*, Vol. 43, No. 2/3/4, Part III, pp. 1713 - 1724, February/March/April 1995.
23. U. Mitra and H.V. Poor, "Neural Network Techniques for Adaptive Multi-user Demodulation," *IEEE Journal on Selected Areas in Communications - Special Issue on Intelligent Signal Processing in Communications*, Vol. 12, No. 9, pp. 1460 - 1470, December 1994.
24. L.B. Nelson and H.V. Poor, "EM and SAGE Algorithms for Multi-user Detection," *Proceedings of the 1994 IEEE/IMS Workshop on Information Theory and Statistics*, Alexandria, VA, October 27 - 29, 1994, p. 70.
25. Y. Steinberg and H.V. Poor, "On Sequential Delay Estimation in Digital Communications Systems," *IEEE Transactions on Information Theory*, Vol. 38, No. 5, pp. 1327 - 1333, September 1994.
26. L.B. Nelson and H.V. Poor, "Soft-decision Interference Cancellation for AWGN Multi-user Channels," *Proceedings of the 1994 IEEE International Symposium on Information Theory*, Trondheim, Norway, June 27 - July 1, 1994, p. 134.
27. U. Mitra and H.V. Poor, "A Projection Based Adaptive Decorrelating Detector for Synchronous CDMA Channels," *Proceedings of the 28th Annual Conference on Information Sciences and Systems*, Princeton University, Princeton, NJ, March 16-18, 1994, pp. 1004-1009.
28. L.A. Rusch and H.V. Poor, "Asymptotic Normality of the Cross-correlation of CDMA System with Phase Drift," *Proceedings of the 28th Annual Conference on*

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Information Sciences and Systems, Princeton University, Princeton, NJ March 16-18, 1994, pp. 449 - 455.

29. L.A. Rusch and H.V. Poor, "Narrowband Interference Suppression in Spread Spectrum Communications via Multiuser Detection Techniques," *Proceedings of the 7th IEEE European Conference on Mobile Personal Communications*, Brighton, UK, December 1993, pp. 84 - 89.
30. U. Mitra and H.V. Poor, "Analysis of an Adaptive Decorrelating Detector for Synchronous CDMA Channels," *Proceedings of the 7th IEEE European Conference on Mobile Personal Communications*, Brighton, UK, December 1993, pp. 155-160.
31. H.V. Poor and S. Verdú, "A Lower Bound on the Probability of Error in Multihypothesis Testing," *Proceedings of the 31st Annual Allerton Conference on Communications, Control and Computing*, University of Illinois, Monticello, IL, September 29 - October 1, 1993, pp. 758 - 759.
32. U. Mitra and H.V. Poor, Invited, "Neural Networks in Adaptive Multiuser Detection," *Proceedings of the 4th International Conference on Advances in Communications and Control*, Rhodes, Greece, June 14-18, 1993.
33. L.B. Nelson, *Multiuser Detection for Radio-frequency and Optical Code-division Multiple Access Channels*.
34. U. Mitra, *Adaptive Multi-user Detection*.
35. S. Verdú, "Adaptive Multiuser Detection," Chapter in *Code Division Multiple Access Communications*, S.G. Glisic and P.A. Leppanen, Eds., pp. 97-116, Kluwer Academic, 1995.
36. S. Verdú and H.V. Poor, "Probability of Error in MMSE Multiuser," *IEEE Trans. on Information Theory*, vol. 43, no. 3, pp. 858-871, May 1997.
37. S. Verdú and A. McKellips, "Worst-case Additive Noise for Binary-Input Channels under Constraints of Variance and Divergence," To Appear.
38. S. Verdú and N. Mandayam, "Analysis of an Approximate Decorrelating Detector," To Appear in *Wireless Personal Communications*, Special Issue on "Interference in mobile Wireless Systems."

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39. S. Verdú and H. Huang, "Linear Differentially Coherent Multiuser Detection for Multipath Channels," To Appear in *Wireless Personal Communications*, Special Issue on "Interference in Mobile Wireless Systems."
40. S. Verdú and H.V. Poor, "A Lower Bound on the Error Probability of Multihypothesis Testing," *IEEE Trans. on Information Theory*, vol. 41, no. 6, pp. 1992-1993, Nov. 1995.
41. S. Verdú, M. Honig and U. Madhow, "Blind Adaptive Multiuser Detection," *IEEE Trans. on Information Theory*, vol. 41, no. 4, pp. 944-960, July 1995.
42. S. Verdú, S. Vembu, R.A. Kennedy and W. Sethares, "Convex Cost Functions in Blind Equalization," *IEEE Trans. on Signal Processing*, vol. 42, no. 8, pp. 1952-1961, Aug. 1994.
43. S. Verdú, "Multiuser Demodulation for CDMA Channels," (Invited Plenary Talk) *Forth Bayona Workshop on Intelligent Methods in Signal Processing and Communications*, Bayona-Vigo, Spain, July 25, 1996.
44. S. Verdú, "An Overview of Multiuser Detection," Invited Talk, *1996 IEEE Workshop on Communication Theory*, Destin, Florida, Apr. 1996.
45. S. Verdú and A. McKellips, "Least-Favorable Divergence-Constrained Noise for Binary-Input Channels," *Proc. Thirty-third Annual Allerton Conference on Communications, Control and Computing*, pp. 608-617, Allerton House, Monticello, IL, Oct. 4-6, 1995.
46. S. Verdú and N. Mandayam, "Analysis of an Approximate Decorrelating Detector," *Proc. Thirty-third Annual Allerton Conference on Communications, Control and Computing*, pp. 1043-1052, Allerton House, Monticello, IL, Oct. 4-6, 1995.
47. S. Verdú, H.C. Huang, and S.C. Schwartz, "Combined Multipath and Spatial Resolution for Multiuser Detection: Potentials and Problems," *Proc. 1995 IEEE Int. Symp. Information Theory*, pp. 380, Whistler, B.C. Canada, Sept. 17-22, 1995.

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48. S. Verdú, "Blind Demodulation for Multiuser Channels," Keynote Address, *Proc. IEEE Signal Processing/ATHOS Workshop on Higher-Order Statistics*, pp. 17-24 Begur, Girona, Spain, June 12-14, 1995.
49. M.L. Honig, S. Verdú and U. Madhow, "Blind Adaptive Interference Suppression for Near-Far Resistant CDMA," *Proc. 1994 Globecom*, San Francisco, CA, vol. 1, pp. 379-384, Nov. 28 - Dec. 1, 1994.
50. S. Verdú and H.V. Poor, "High-speed Digital Signal Processing for Satellite Communications," *Fourth Intl. European Space Agency Workshop on Digital Signal Processing Techniques Applied to Space Communications*, King's College, London, England, Sep. 26-28, 1994.
51. S. Verdú, "Adaptive Multiuser Detection," Invited Paper, *Proc. IEEE Third Int. Symposium on Spread Spectrum Techniques and Applications*, Oulu, Finland, July 4-6, 1994, vol. 1, pp. 43-50.

D. Participating Scientific Personnel

- H.V. Poor (Co. P.I.)
- S. Verdú (Co. P.I.)
- Urbashi Mitra (Ph.D. awarded 1994)
- Laurie Nelson (Ph.D. awarded 1995)
- Adnrew McKellips (Ph.D. expected 1998)
- Howard Huang (Ph.D. awarded 1995)

E. Patents Awarded

None.